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January 1962

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AVROCAR FLIGHT EVALUATION

WALLACE H. DECKERT
1st Lieutenant, USAF
Project Engineer

WALTER J. HODGSON
Major, USAF
Project Pilot

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**AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE**



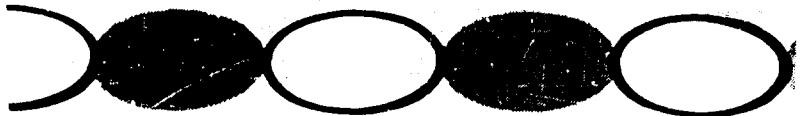
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ABSTRACT



Limited qualitative evaluations of the performance, stability, and control characteristics of the Avrocar, U.S. Army VZ-9AV, were conducted at the contractor's facility in Malton, Ontario, Canada. The first evaluation of the Avrocar, equipped with the focussing ring control system, was conducted on 4 April 1960. Early in 1961, the Avrocar was extensively modified to incorporate a separate control system for transition and high speed flight while retaining the focussing ring control for hovering flight. A second evaluation was conducted on 9 June 1961 to determine if the modifications changed the behavior of the aircraft in the hovering and low speed regime. This report covers the results of both evaluations.

The Avrocar, manufactured by Avro Aircraft, Limited, is an unconventional aircraft having a circular planform. Take-off gross weight is 5680 pounds which includes 840 pounds of fuel and a 190 pound pilot. Three Continental J69-T-9 engines, each rated at 927 pounds static sea level thrust, act as a gas generator to drive a centrally located turborotor. Air from the turborotor flows through radial ducts and exhausts to the atmosphere through various combinations of annular nozzles and peripheral jets, depending on the flight regime. Control is achieved by deflecting a focussing ring and various vanes in the jet efflux. The turborotor is mounted on a spherical bearing and is allowed to move freely within a very small angle (about 1/4 degree) normal to its axis. The gyroscopic precessional motion is coupled to the flight control system to give the vehicle automatic stability augmentation.

At the present time, ground cushion effect provides more than one-half of the lift. The flight envelope is presently limited to a 2 foot hovering height and a maximum airspeed of approximately 20 knots.

Incorporation of the high speed flight control system adversely affected the performance and controllability of the Avrocar during hovering and low speed flight. Hovering performance decreased slightly, longitudinal and lateral control power decreased greatly, longitudinal-directional control coupling is now severe, maximum airspeed decreased from 30 to 20 knots, and ground cushion instability occurs at a lower height. Ground cushion instability occurs at the unstable ground height (critical height) and manifests itself by the aircraft pitching and/or rolling in an unpredictable, uncontrollable manner. Control forces and dynamic stability characteristics were not changed appreciably.

The Avrocar was flown over unprepared and irregular terrain. A relatively large ditch was successfully crossed. However, recirculation of debris is a major problem.

It was evident from asymmetric power tests that control limits would be reached if one of the three engines failed.

None of the deficiencies noted seriously compromise research and development testing at airspeed from 0 to 15 knots. Modifications to the control system and the propulsive system will be necessary before a ground effect transition into high speed forward flight can be demonstrated.

This report
has been
reviewed
and
approved

Charles E. Yeager Col

for CLAYTON L. PETERSON
Colonel, USAF
Director, Flight Test

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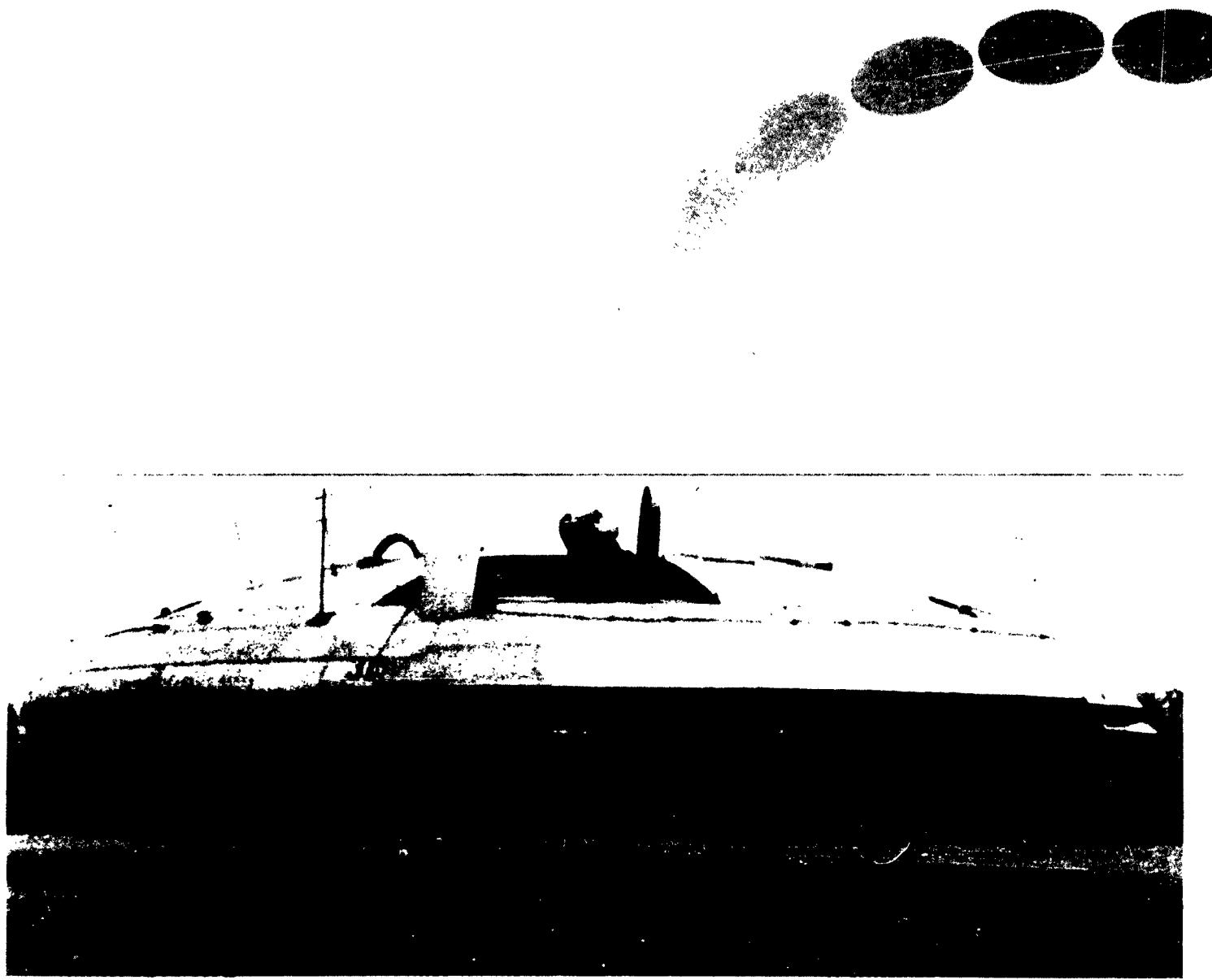
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**AVROCAR HOVERING ABOUT
1 FOOT ABOVE THE CONCRETE**

Qualitative performance, stability and control tests were conducted on the Avrocar, designated U.S. Army VZ-9AV, at the contractor's facility at Malton, Ontario, Canada. Two AFFTC evaluations, each consisting of three test flights, were conducted. No test instrumentation was installed in the vehicle. The first evaluation was on 4 April 1960 and the second evaluation was on 9 June 1961. (A 1)¹

The Avrocar program started with a Request for Proposal dated 18 March 1958. Avro Aircraft Limited proposed a new type of air vehicle suitable for operating close to the ground and capable of vertical take-off and landing, flight to 10,000 feet altitude, and speeds in excess of 200 mph. Under USAF Contract AF 33(600)-3796, one prototype aircraft, designated U.S. Army VZ-9AV, was built and rolled out in May 1959.

The first Avrocar underwent a 32 hour static rig test program at Malton, Canada, from 9 June to 7 October 1959. This aircraft was shipped to NASA (Ames) for full scale wind tunnel tests. The first wind tunnel program in April 1960 consisted of 36 hours of testing the focussing ring configuration. The second wind tunnel program in April 1961 consisted of 54 hours of testing the modified focussing ring-jet flap configuration. Contractor and NASA data show that ground cushion effect provides more than one-half of the lift for this vehicle.

Supplemental Agreement No. 1 in March 1959 authorized the fabrication of a second Avrocar, which was rolled out in August 1959.

The first free flight, which was conducted on the second vehicle, was on 12 November 1959. At this time, the aircraft was fitted with the original nozzle spoiler control system (Fig. 1). Two continuous rings or spoilers were fitted in the throat of the annular nozzle. The projection of the spoilers controlled the direction of the jet efflux. The spoiler control produced pitching and rolling moments by destroying lift on one side and not creating more lift on the opposite with the result that the aircraft lost height during maneuvering flight. Since the lift loss was greater than expected, the spoiler control was replaced with a focussing ring control.

Free flights with the focussing ring control began in January 1960. The lift loss during maneuvering flight was reduced, but the focussing ring control was unsatisfactory for high speed forward flight.

The first AFFTC evaluation consisted of one tethered familiarization flight and two free test flights for a total flight time of 45 minutes. The purpose was to evaluate the general flying qualities of the Avrocar equipped with only the focussing ring control system.

Full scale wind tunnel tests in April 1960 showed that (1) the focussing ring could not sufficiently divert the jet thrust in an aft direction, (2) a large nose-up pitching moment existed at forward speed, (3) large positive angles of attack were required to generate lift forces equal to aircraft weight because of a low value of lift curve slope, and (4) a rolling moment and side force of appreciable magnitude resulted from the intake flow entering the turborotor non-vertically at forward speed.

¹ Numbers indicated as (A1), etc., represent the corresponding recommendation numbers as tabulated in the Recommendation Section of this report.

CONTROL MECHANISM COMPARISON

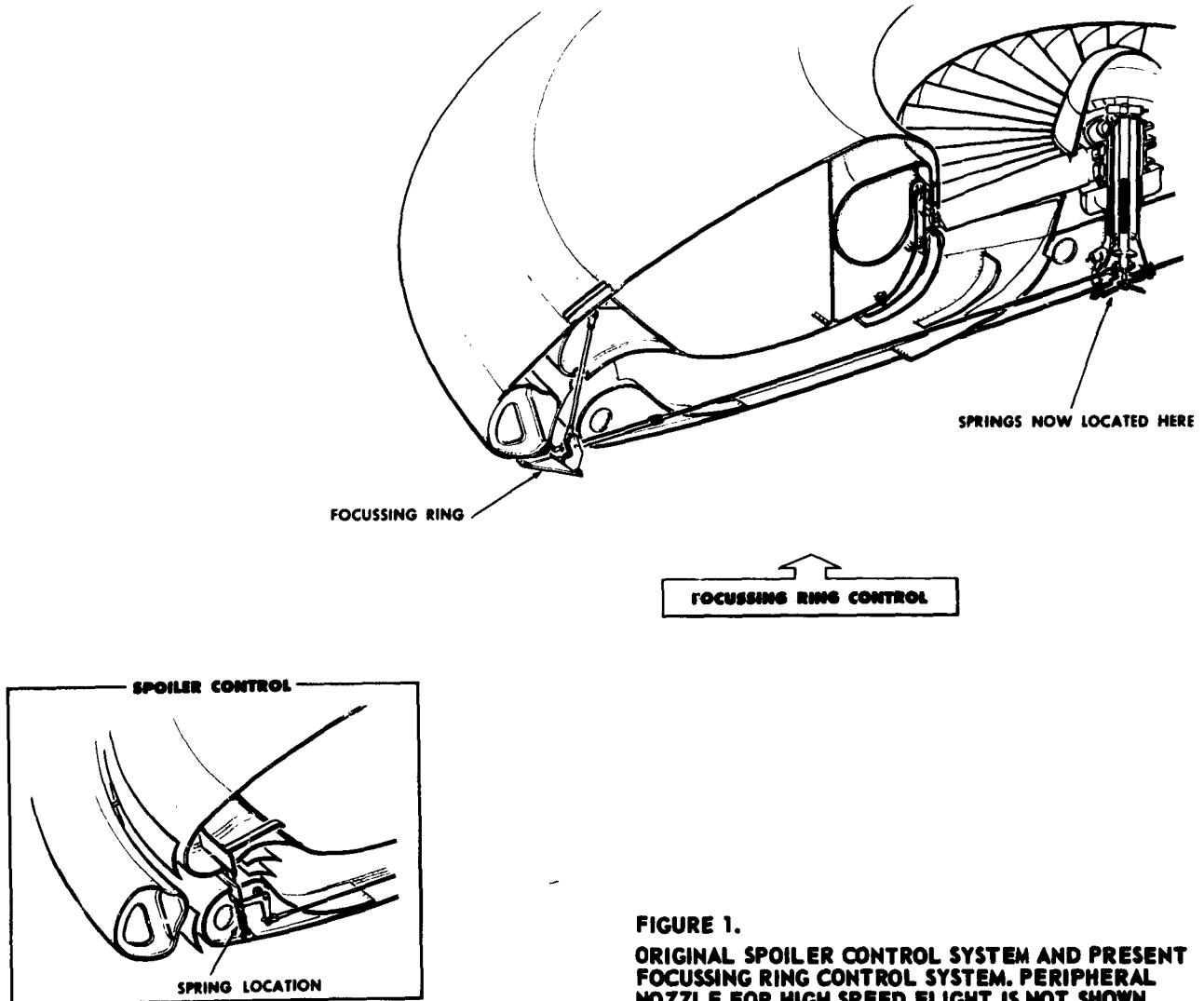


FIGURE 1.
ORIGINAL SPOILER CONTROL SYSTEM AND PRESENT
FOCUSING RING CONTROL SYSTEM. PERIPHERAL
NOZZLE FOR HIGH SPEED FLIGHT IS NOT SHOWN.

As a result of these tunnel tests, the control system of the Avrocar was extensively modified. A separate high speed flight control system was installed which consists of a new peripheral nozzle about the rear half of the aircraft with various transition doors, vanes, and cascades described in detail under Description of the Aircraft.

The program under which the revised high speed flight control system was made was called the Avrocar Continuation Test Program, USAF Contract AF 33(600)-42163, and covered the period from July 1960 to June 1961.

Full scale wind tunnel tests, conducted in April 1961, indicated that a GETOL (Ground Effect Take-Off and Landing) transition into forward flight out of ground effect was feasible. According to tunnel tests, trim was available from hovering flight to about 100 knots IAS. Wind tunnel test results also indicate that sufficient control is available to conduct a transition into high speed flight (about 100 knots maximum), provided that 35 to 40 knots can be obtained with the focussing ring control.

In April 1961, the contractor initiated a 12-hour flight test program on the second aircraft to determine (1) if the new forward flight control system had adversely affected the focussing ring hovering control system, and (2) the effects of flying over unprepared and irregular terrain. The second flight evaluation by AFFTC personnel on 9 June 1961 was limited in scope to determination of these two factors.

The second aircraft has logged a total of about 75 hours.

The Avrocar Continuation Test Program was concluded with a general review on 13 and 14 June 1961.

DESCRIPTION OF THE AIRCRAFT

This section describes the Avrocar in the configuration tested on 9 June 1961. The section also pertains to the configuration tested on 4 April 1960, with the exception that the high speed flight control system had not been incorporated in the aircraft, the yaw vanes were located on the lateral axis, and the gross weight was approximately 5250 pounds.

■ GENERAL

The Avrocar is an unconventional aircraft having an 18 foot diameter circular planform. A one-place open cockpit is located on each side of the aircraft. A fixed tricycle landing gear with 6 inch diameter wheels is provided. (Landing gear pads have also been used for landing on soft terrain.) Take-off gross weight is 5680 pounds, which includes 840 pounds of fuel (3/4 capacity), and a 190 pound pilot.

Three Continental J69-T-9 engines, each rated at 927 pounds static sea level thrust, act as a gas generator to drive a centrally located turbine-compressor combination known as a turborotor. Air from the 60 inch diameter turborotor (and the J69 exhaust) flows through 54 radial ducts and exhausts to atmosphere through various combinations of annular nozzles and peripheral jets, depending on the flight regime.

■ HOVERING FLIGHT

For hovering and low speed flight, air is exhausted out of the bottom of the aircraft from three locations, an inner set of exhaust jets, a middle set of exhaust jets, and a continuous annular nozzle about the periphery. Most of the air flows through the annular nozzle.

Hovering height is controlled with the throttles. Throttle position determines J69 engine power which in turn determines the turborotor speed and, therefore, the air mass flow. Turborotor collective pitch is not provided. The internal ducting to the inner jets, middle jets, and annular nozzle is not variable. Only the total mass flow can be controlled from the cockpit and not the mass flow components through the various jets and nozzles.

A focussing ring (Figs. 2 and 3) is located in the exhaust of the annular nozzle. The focussing ring is attached to the upper body structure by 18 links symmetrically positioned around the periphery. Bearings in the ends of the attachments permit the focussing ring to be moved in any horizontal direction. Longitudinal and lateral control is obtained during low speed flight by displacing the focussing ring as shown in Fig. 2. A pneumatic boost is incorporated in the control system.

Yaw control vanes (Fig. 3) are located forward of the lateral centerline of the vehicle and upstream of the annular nozzle. The yaw vanes are operated by pneumatic jacks.

■ TRANSITIONAL AND HIGH SPEED FLIGHT

For transition and high speed flight, an alternate flow for the jet efflux is provided. A peripheral nozzle, extending from the radial ducts, is located around the rear half of the wing tip structure. Fixed cascades at the radial extremities direct the jet flow in a rearward and slightly outward direction.

FOCUSING RING CONTROL POSITIONS

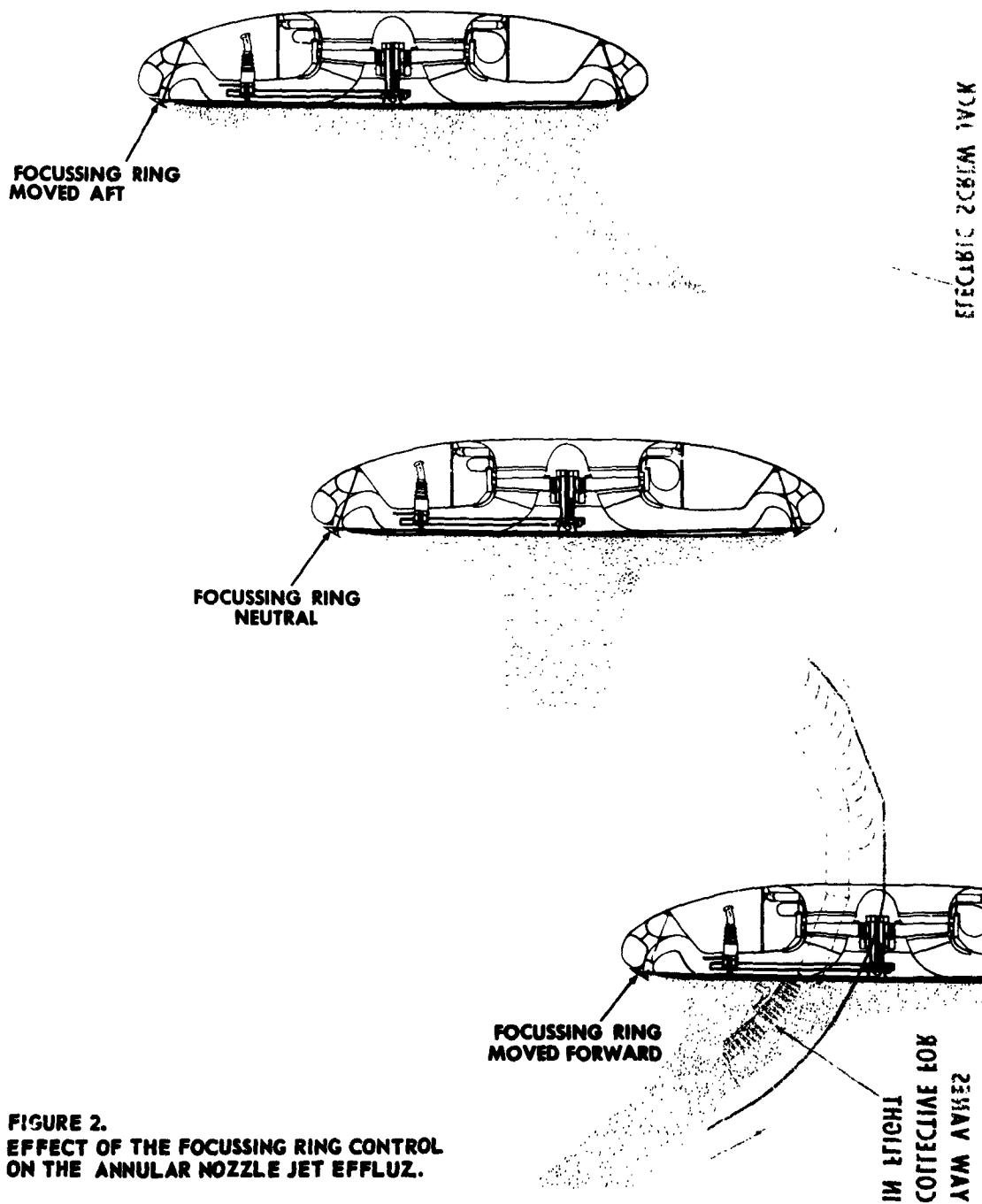
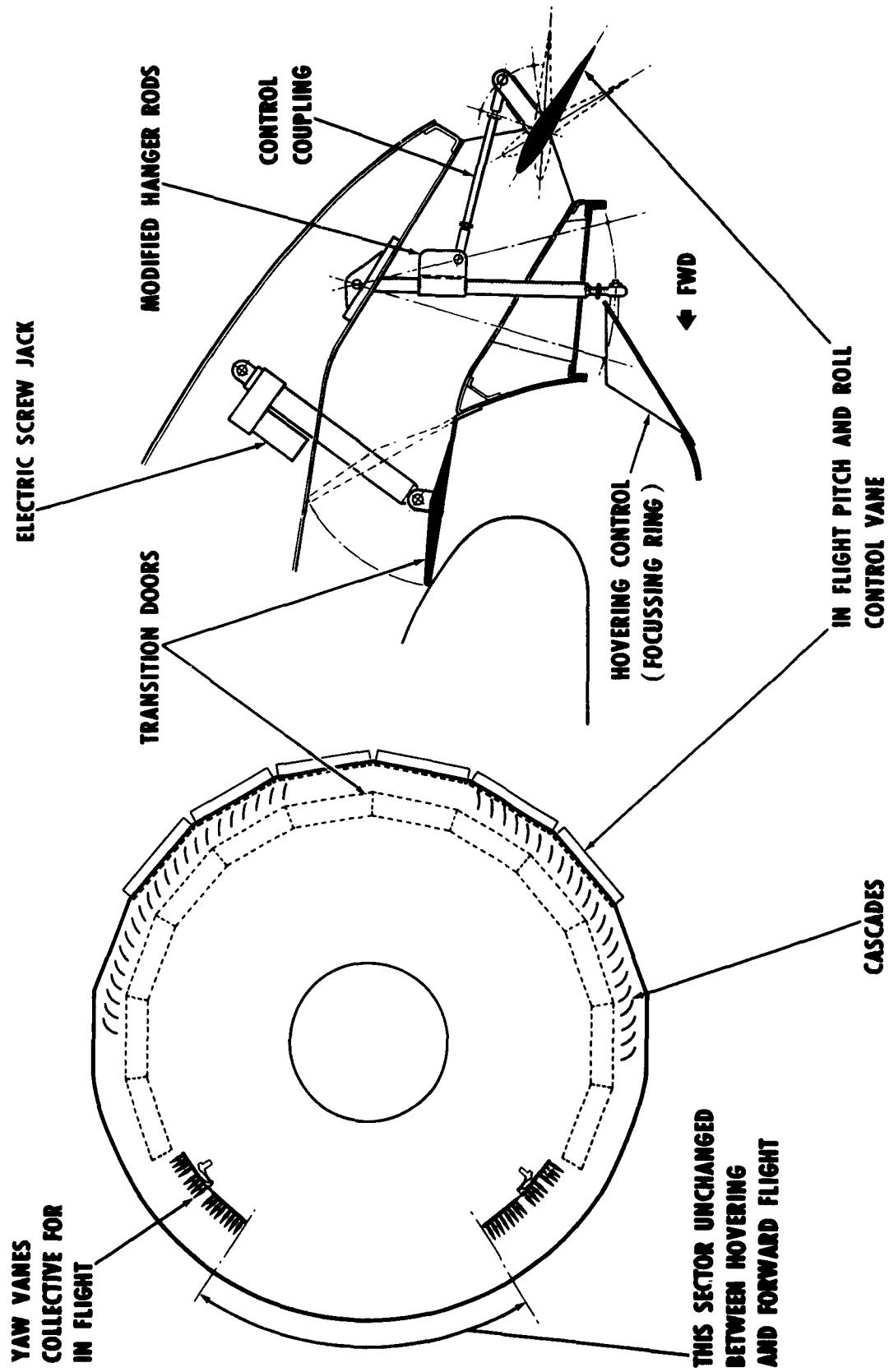


FIGURE 2.
EFFECT OF THE FOCUSING RING CONTROL
ON THE ANNULAR NOZZLE JET EFFLUZ.

FIGURE 3.
AVROCAR CONTROL SYSTEM.



Flow splitters, called transition doors, direct the jet flow through either the peripheral or the annular nozzle. The twelve transitional doors are hinged at their lower outboard edge and are operated by electric screw jacks.

With the transitional doors open, a jet sheet or jet flap extends from the rear of the aircraft. Six vanes, each occupying 20 degree segments at the rear 120 degrees of peripheral nozzle, control of the jet flap. These six vanes are hinged and coupled to the control system in such a manner as to operate in conjunction with the focussing ring control (Fig. 3).

■ AUTOMATIC STABILIZATION SYSTEM.

The turborotor, which acts as a large gyroscope, is mounted on a spherical bearing and is allowed to move freely within a very small angle (about 1/4 degree) normal to its axis. The gyroscopic precessional motion is coupled into the flight control system to give the vehicle automatic stability (Fig. 4). (B 6)

The relative motion of the gyro is stepped up, with a mechanical linkage, into the central control post which is connected to the focussing ring through a number of cables. When the aircraft is pitching or rolling, the gyro applies a stabilizing control input. The pilot control input, which also acts on the central control post through pneumatic bellows, overrides the gyro input.

TURBOROTOR SHAFT ASSEMBLY

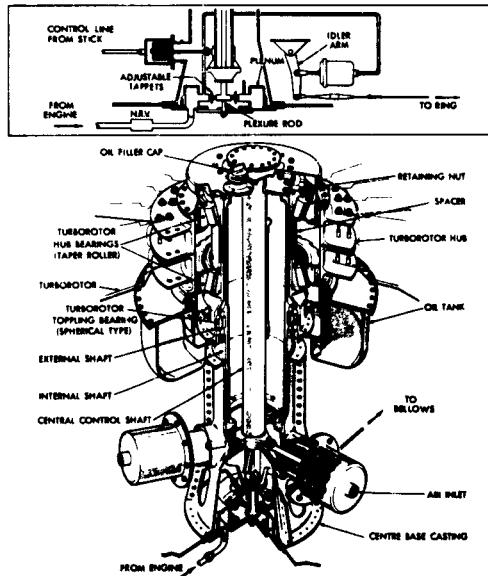


FIGURE 4.
**TURBOROTOR SHAFT ASSEMBLY AND
DIAGRAM SHOWING CENTER CONTROL
POST AND PNEUMATIC CONTROL SYSTEM.**

TEST RESULTS

■ COCKPIT EVALUATION

The Avrocar is a research vehicle. Research and development testing is not compromised because of cockpit dimensions, controls, instruments, or environmental factors. Therefore, the cockpit is considered satisfactory. The cockpit would be deficient in several areas if the Avrocar were a production vehicle. A discussion of these deficiencies is included for future considerations.

Each cockpit is offset approximately 17 degrees from the longitudinal axis because of structural and space limitations. The slope of the upper surface of the fuselage results in an erroneous impression of fuselage attitude and height above the ground and also restricts visibility to the right. While accelerating into forward flight, the pilot is tilted to the left as well as forward. The orientation of this symmetrical aircraft is arbitrary while flying in the hovering or low speed regime. However, if the aircraft is oriented so that the pilot flies straight forward, the copilot will be in a 34 degree sideslip. A two place cockpit, located on and aligned with the longitudinal axis of the aircraft, should be provided on a production aircraft. (A 4)

The engine instruments are located on the left side of the cockpit above and adjacent to the throttles (Fig. 5). The engine instruments are difficult to monitor because of their location and because of a large parallax. Ease of monitoring engine instruments is a major factor since ground height, control power, and aircraft stability are dependent on the power setting. The engine instruments should be located in a more visible area in front of the pilot.

A control stick, which extends about 14 inches above the pivot point, is located in front and to the right of the pilot as shown in Fig. 6. The control

stick is displaced in a conventional manner for longitudinal and lateral control. Directional control is obtained by rotating the control grip. Additional clearance is required between the control grip and the right bulkhead. Right lateral control is limited because the back of the hand contacts the bulkhead prior to reaching full right control displacement. Directional control should be provided by conventional foot pedals. It is difficult to rotate the control grip without radially displacing the control stick. Consequently, lateral and/or longitudinal inputs are inadvertently induced during directional inputs. When the directional control is rotated to the left, lateral control is further reduced because the wrist contacts the right bulkhead. (A 5)

Cockpit temperatures are very high and would be unsatisfactory in a prototype, or even in a research aircraft, if long flights were required. The foot wells, right bulkhead, and throttles become exceedingly hot during a 15 minute flight.

A cockpit canopy should be installed to afford protection from debris such as grass, moisture, and sand. A device to remove moisture and debris from the canopy is also required to insure visibility. A modified oxygen mask and visor, must be worn in the open cockpit of the Avrocar. The mask and visor, even when clean, restrict visibility of the engine instruments. When flying over unprepared terrain or puddles of water on concrete surfaces, the visor is immediately covered with debris and/or moisture which severely restrict visibility. Installation of a protective canopy must be preceded with a reduction of cockpit temperatures.

■ ENGINE START AND TAKE-OFF.

The procedure for starting the engines is quite simple. A switch is

provided to select the engine to be started (Fig. 6). A starter switch is actuated, at 10 percent rpm the ignition switch is actuated, and the throttle is advanced to the GROUND IDLE position. At 20 percent rpm the ignition and starter switches are turned OFF. The procedure is then repeated for the next engine. All three engines can be started in less than 1 minute and engine warm-up is not required. The generators are turned ON at 50 percent rpm, ground power is removed, and the aircraft is ready for take-off.

Engine speed is increased to approximately 66 percent prior to take-

off. Just above 66 percent, the thrust to weight ratio is nearly one and the aircraft rolls on its wheels if disturbed by wind. The ground roll can be stopped only by reducing power.

To assure that adequate control power is available during take-off, the power required for hovering must be added rapidly. Control power is a function of mass flow through the annular nozzle and the mass flow is dependent on engine power. Control is marginal for throttle settings below 85 percent rpm. The engine speed is set at 66 percent prior to take-off to minimize the throttle movement required to rapidly reach 85 percent. (B 3)

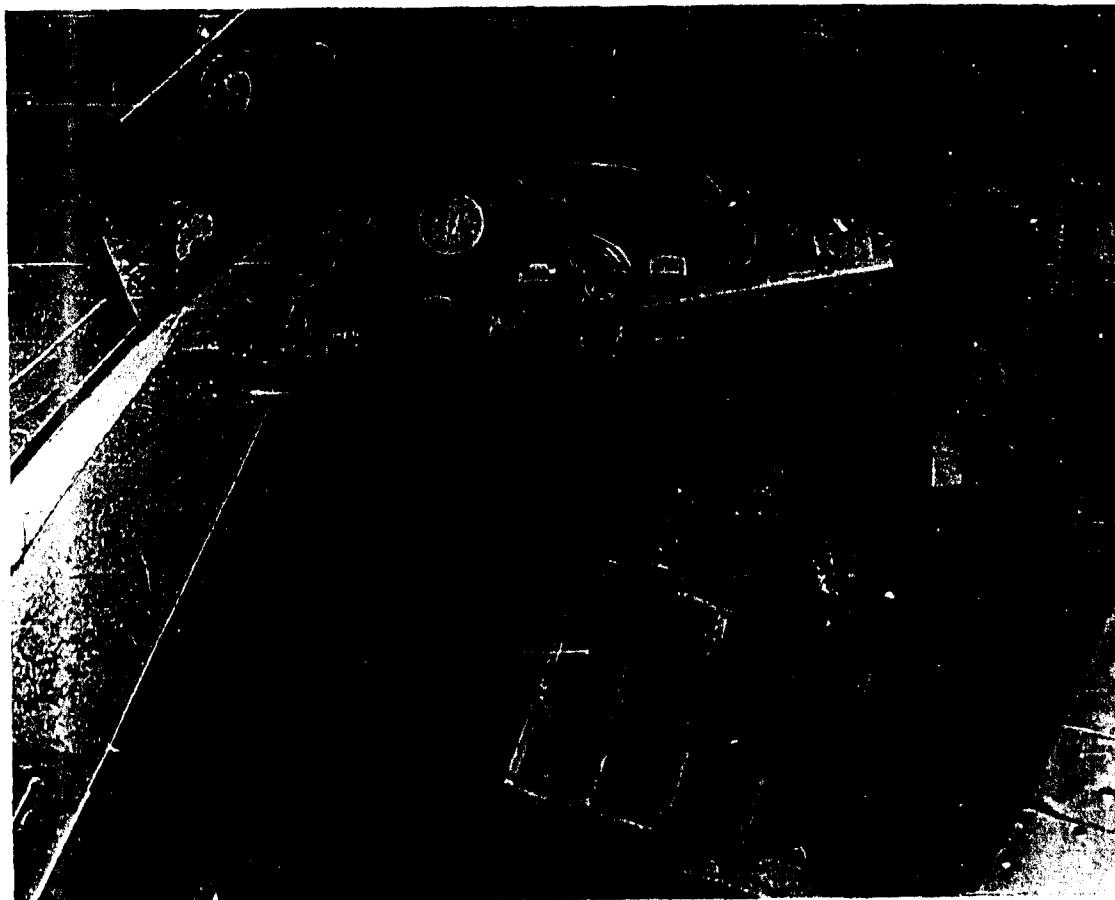


FIGURE 5
VIEW OF COCKPIT AFTER FLIGHT OVER
GRASSY AREA. ENGINE INSTRUMENTS
ARE LOCATED ON SIDE PANEL ABOVE
THROTTLES



FIGURE 6
VIEW OF COCKPIT SHOWING CONTROL
STICK WITH ROTATING GRIP AND THE
THREE TRIM CONTROLS

In calm wind, the aircraft lifts off vertically and slowly yaws to the left. When winds are present, the aircraft will drift downwind until adequate control power is available to overcome this drift. Thus, the rapidity with which power must be added to obtain control during take-off varies with the wind velocity. (B 9)

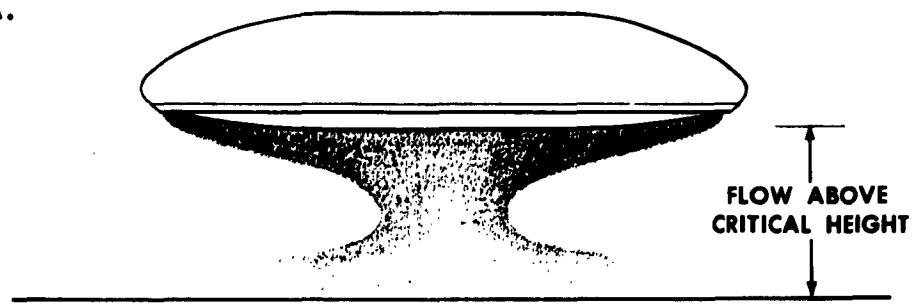
If too much power is added during the take-off, the aircraft will reach a ground height that results in an unstable ground cushion. The unstable ground height, about 2 feet from the bottom of the wheels to the ground, is called the critical height (Fig. 7). At critical height, the aircraft pitches and/or rolls in an unpredictable, uncontrollable manner. The motion is rapid, and is

usually an oscillatory, coupled motion about the longitudinal and lateral axes. The motion is termed "hubcapping." At critical height, control inputs are effective only in controlling the general flight path of the aircraft. Control inputs do not appear to aggravate the erratic instabilities caused by the ground cushion. (B 1, A 3)

Because of the control power and critical height problems, take-off must be accomplished by rapidly advancing the throttles from 66 percent rpm to a relatively narrow rpm band (between 85 and 95 percent). The inability to satisfactorily monitor the engine instruments while rapidly advancing the throttles is disturbing. After familiarization, it was found practical to add

JET FLOW REGIMES IN AREA OF CRITICAL HEIGHT

A.



B.



C.

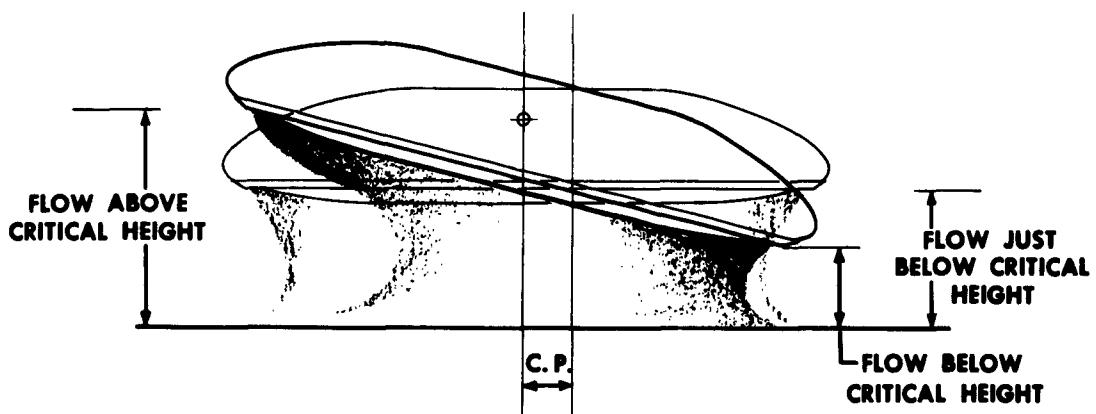


FIGURE 7
DIAGRAM ILLUSTRATING THE CAUSE OF
GROUND CUSHION INSTABILITY AT THE
CRITICAL HOVERING HEIGHT

power until a satisfactory ground height was obtained and then to stabilize the aircraft to observe and adjust the engine power.

■ HOVER

The aircraft is controllable at heights between 1 and 1½ feet (distance from bottom of the wheels to the ground). Critical height in the present configuration is about 2 feet, which is approximately 6 inches lower than that obtained during the first evaluation.

The center of gravity was located on the axis of the turborotor for the tests. This was accomplished by utilizing ballast in the right cockpit. (B 3, B 4)

The engine speed required to maintain a hovering height of 1½ feet is 91 percent, compared to 89 percent required during the first evaluation. The corresponding turborotor speeds are 2150 and 1850 rpm. The degradation of the hovering performance is attributed primarily to decreased duct efficiency resulting from incorporation of the new high speed flight control system and increased gross weight (about 400 pounds). The duct efficiency decreased because the transition doors compromise the contour of the duct. As a result of the transition doors not being sealed some air escaped into the peripheral nozzle during hovering flight. The repeated ingestion of debris through the three circular ducts evenly spaced on the top of the fuselage, may also have reduced engine power available. (A 3)

Control travel is satisfactory. Full longitudinal and lateral control travel is 3 inches from neutral in all directions. Full directional control travel is approximately +40 degrees.

The longitudinal and lateral control force gradient is approximately 5 pounds per inch deflection. Six 15-pound springs center the focussing ring control. As a result of the strong centering, corrective control inputs during hovering flight are normally small pulses from the neutral

control position. Therefore, the high control forces are satisfactory for short hovering flights.

A system for trimming the aircraft about each axis is provided. Since the trim control system is an integral part of the primary control system, trim control reduces the total control power available. The trim control is too sensitive, but satisfactory for a research vehicle.

Longitudinal and lateral control power is much less than that obtained during the first evaluation. A modified focussing ring suspension system (Fig. 3) was incorporated in the aircraft which increased the hinge moment of the focussing ring. To overcome the higher hinge moment, the plenum chamber pressure of the pneumatic control system was increased from 20 to 30 psi. The increased plenum chamber pressure does not fully compensate for the high hinge moment and, consequently, the travel of the focussing ring is less than that obtained previously. (B 5, A 2)

Longitudinal and lateral control response following small control inputs is satisfactory. Only the total control power (or total focussing ring travel) has been reduced. The response following longitudinal or lateral control inputs is not noticeably manifested by aircraft responses about any other axis.

Directional control is deficient in several respects. During the first evaluation, no pitch or roll coupling resulted from directional control inputs and directional control response was similar in either direction. The aircraft now exhibits severe longitudinal-directional control coupling. A directional control input produces a rapid nose down pitching. The coupling is considered to be due to the relocation of the yaw control vanes which were moved from the original lateral location to the forward section of the aircraft. It is believed that, when the yaw vanes actuate, the forward portion of the ground cushion is temporarily disturbed,

resulting in a loss of lift and nose down pitching moment.

Directional control power is much weaker to the right than to the left. The yaw vanes stick following a left yaw input and right yaw control is required to center the vanes. The jamming of the yaw vanes may have been due to debris entering the yaw vane actuators during flights over unprepared terrain.

Directional control response is poor if the control grip is rotated at a normal rate. For adequate directional control, it is necessary to make rapid control inputs and monitor the yaw vane position. Following a full directional control deflection to the left, the aircraft immediately pitches nose down and there is no directional response for at least 1 second. The aircraft turns 90 degrees in approximately 5 seconds after a full directional control input to the left. Approximately 11 seconds is required for a 90 degree right turn. No directional response resulted from a 1 second, full deflection, directional control pulse.

The longitudinal or lateral control power is reduced if a directional input is initiated prior to displacing the control stick. The focussing ring rotates when directional control is applied, which may increase the hinge moment and/or bind the controls. The focussing ring can be jammed by manually rotating it in the longitudinal-lateral plane. The ring contacts the skirt assembly which was added to the annular nozzle to reduce thrust losses. The interferences could be eliminated by reducing the width of the skirt as required.

There is no noticeable damping in yaw. Control inputs are constantly required to maintain a heading within ± 20 degrees. When maintaining a heading is not a requirement, the aircraft may be allowed to slowly rotate to reduce the longitudinal-directional control coupling.

The optimum hovering height is selected by compromising control

power and ground cushion stability. At low hovering heights, the ground cushion is stabilizing but control power is poor. As hovering height increases, control power improves but the ground cushion becomes unstable. At the optimum hovering height, the aircraft is continually oscillating (or hubcapping) because of a mild ground cushion instability. The ground cushion instability is not highly objectionable because initially the instability is mild and as the pitching and/or rolling amplitudes increase, the ground height decreases slightly which increases ground cushion stability. (B 2)

A concentrated effort is required to stabilize the aircraft completely for short periods in calm wind. Hands-off flight is possible for several seconds if the aircraft is allowed to very slowly translate and/or rotate.

Noise levels are very uncomfortable and are comparable to those in the propeller plane in the fuselage of the C-130A in cruise flight. High frequency noises are predominant, resulting in a noise similar to that of a siren. Ear protection is mandatory for ground personnel as well as the pilot.

Vibration levels are low, similar to those encountered in fixed-wing turbine aircraft.

■ LEVEL FLIGHT

The maximum airspeed that could be obtained during the first evaluation was 25 to 30 knots. At this speed a longitudinal pitching oscillation was encountered which could not be damped by control applications.

In the present configuration, the aircraft can be accelerated to a maximum of 15 or 20 knots. A slightly higher airspeed may be obtainable in calm air, however, a slight gust will cause the aircraft to pitch up and the remaining control that is available at 15 knots must be utilized to control the pitching rather than for accelerating to a higher airspeed. (B 9)

The decrease in maximum airspeed is a result of the decreased travel of the focussing ring.

Longitudinal and lateral control forces in level flight are high. The right lateral control force is excessive. The magnitude of the left and right lateral forces is the same, but it is more difficult to exert forces to the right. Since the control stick is located on the right side of the cockpit, lateral control inputs are made primarily by pivoting the arm and wrist about the elbow. Consequently, identical lateral forces seem much higher to the right. In a production vehicle the right lateral force should be reduced so that it seems equivalent to the left lateral force.

The directional control forces are less than those encountered during the first evaluation. However, the right directional control force is still difficult to overcome because of the wrist action required.

Lateral as well as longitudinal control power has been markedly reduced. The aircraft was flown in 12 to 15 knot winds during the first evaluation. A control stop was encountered in only one case during maneuvering flight. During the second evaluation, full control deflections were required numerous times during maneuvering flight in 5 to 10 knot winds.

Left directional control power is similar to that obtained during the first evaluation, but right directional control is much weaker.

The aircraft yaws slightly to the right when accelerating from hovering flight into forward flight. Corrective left directional control results in nose down pitch which prohibits a smooth transition into forward flight.

During forward flight the control stick must be held forward to maintain the desired attitude. (A neutral control position can be utilized in forward flight by use of trim control.) If the control stick is returned to neutral, the aircraft will assume a slightly nose high

attitude, rather than a level attitude, and slowly decelerate.

■ ASYMMETRIC POWER

Tests were conducted to determine the effect of asymmetric power during hovering and very low speed flight.

Hovering flight was established with all three engines set at 90 percent rpm and a turborotor speed of 2150 rpm. Number One engine speed was slowly decreased to 70 percent while Number Two and Three engine speed was increased to 96 percent to maintain the turborotor rpm at 2150 and a constant ground height. As Number One engine power was decreased, the plenum chamber pressure, which is directly related to control power, decreased from 30 to 28 psi. The frequency of the turborotor speed fluctuations about 2150 rpm decreased and the amplitude of the fluctuations increased from ± 50 to ± 100 rpm. The most pronounced effect of this asymmetric power condition is that a large amount of aft control (near the aft stop) and some left lateral control is required to maintain hovering flight.

The identical procedure was used in reducing Number Two engine power while increasing Number One and Number Three engine power. Results were similar to those of the previous test except left lateral and forward control was required to maintain hovering flight. It was not possible to reduce Number Two engine speed to less than about 80 percent before control limits were reached. However, a 5 to 8 knot wind was shifting and gusty; this may have had an influence on the control required.

The effect of reducing power on Number Three engine was not determined because of time considerations and lack of satisfactory right lateral control.

Means of minimizing control changes as a result of an asymmetric power condition should be determined. However,

it is possible that asymmetric power could be used during a research program to increase control power in a desired direction. (B 4)

■ EFFECTS OF UNPREPARED IRREGULAR TERRAIN

One 14 minute flight was conducted to determine the effect of flying over unprepared, irregular terrain. The Avrocar was flown over light gravel, dirt, green and dead grass, small water puddles, a relatively large ditch, a narrow ditch, and a sharp one foot step.

While hovering or slowly translating, recirculation is very pronounced. Debris is recirculated into the turborotor, engine in-takes, cockpit, and all around the aircraft. On this flight the debris consisted of bits of grass (both green and dead), sand, dirt, twigs, various pieces of paper and cardboard.

Complete eye protection is an absolute necessity. A helmet with a modified oxygen mask and a sealed visor was worn. Small particles still entered a small opening under the visor. Flight over water puddles resulted in a mist that completely restricted visibility until the water was depleted from the puddle. Recirculating dust and dirt also severely restricted visibility. (B 10)

Screens were not installed in the engine intakes for this flight. Previous flights, conducted by the contractor with screens installed, were unsatisfactory because recirculating debris quickly clogged the screens, resulting in engine starvation. The engines satisfactorily digested debris on this flight. However, it is evident that some form of engine protection will be required to prevent engine deterioration of an operational vehicle.

Recirculating debris also entered the unprotected turborotor. Though the turborotor did not incur visible damage as a result of this flight, it is evident that turborotor protection will also be required.

Another problem may be encountered while conducting a ground effect take-off in a vehicle similar to the Avrocar. During take-off over some types of unprepared terrain, mud will accumulate on the circular wing and ruin the airfoil characteristics. (B 7)

As forward speed is increased to about 10 to 15 knots, most of the circulating debris trails the Avrocar. It appears that circulating debris will not affect the aircraft at higher forward speeds; however, the downwash and circulation will be undesirable for flight within the ground cushion at any speed because of damage to vegetation and objects on the ground, and because the flying debris will clearly indicate the location of the vehicle.

Dead grass was not scorched during about 1 minute of hovering flight. Occasionally a smell of burning grass was noted, apparently due to debris entering the engines. Though this brief test is inconclusive, the starting of grass fires may not be a major problem.

Approximately 1 percent additional engine speed was required to maintain an adequate ground height over grassy areas as compared to concrete or hard ground. Stability and control characteristics were not noticeably affected by the unprepared level terrain.

The Avrocar was flown very slowly over an abrupt 1 foot rise in ground height. Power was held constant. The altitude of the Avrocar remained essentially constant until 1/2 to 2/3 of the fuselage was over the step. Then the Avrocar suddenly rose 1 foot in a near vertical translation. Pitching oscillations were mild. Similar results were obtained when crossing the step from the higher elevation to the lower elevation. It was surprising to note that at very low airspeed the Avrocar was approximately 2/3 across the step before altitude was lost or gained. (B 8)

A small ditch (about 1 to 2 feet wide and 1 to 1 1/2 feet deep) was crossed at about 10 knots airspeed with the flight

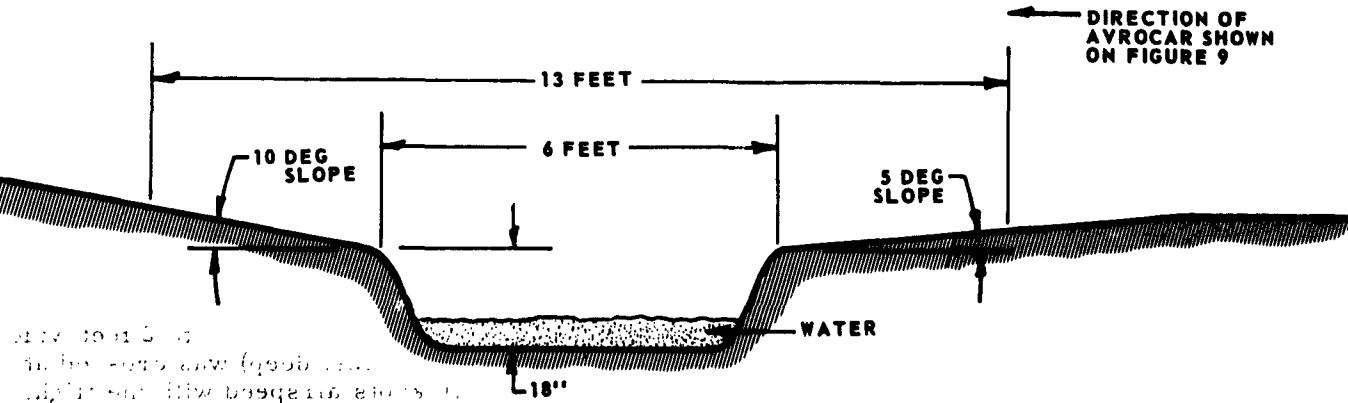
path perpendicular to the ditch. The only result was a minor, transient pitch change.

A large ditch, compared to the size of the Avrocar, was successfully crossed. The dimensions of this ditch are shown on Fig. 8. The ditch was approached at about 10 knots airspeed and at the optimum ground height (1 to 1½ feet). When the fuselage was about ½ over the first edge of the ditch (Fig. 9), the aircraft began to nose down into the ditch. As soon as the aircraft began to nose down, the longitudinal control was neutralized. When the fuselage was almost across the first edge of the ditch, the aircraft began to nose up. As the front of the aircraft began to rise, full forward (nose down) control was rapidly applied. As soon as the nose stopped going up the control was again neutralized. The pitch attitude changes were not considered excessive.

The large ditch was crossed twice. At no time did the wheels or any part of the fuselage contact the ground. However, the focussing ring control nearly contacted the ground. The focussing ring on the Avrocar is not protected by bumpers, a guard ring or equivalent protection. The test illustrated that relatively large ditches could be successfully crossed while operating in ground effect, but that a primary control, such as a focussing ring, must be protected. (A 6)

**FIGURE 8
DIMENSION OF LARGE DITCH**

NOTE: DIAMETER OF AVROCAR - 18 FEET



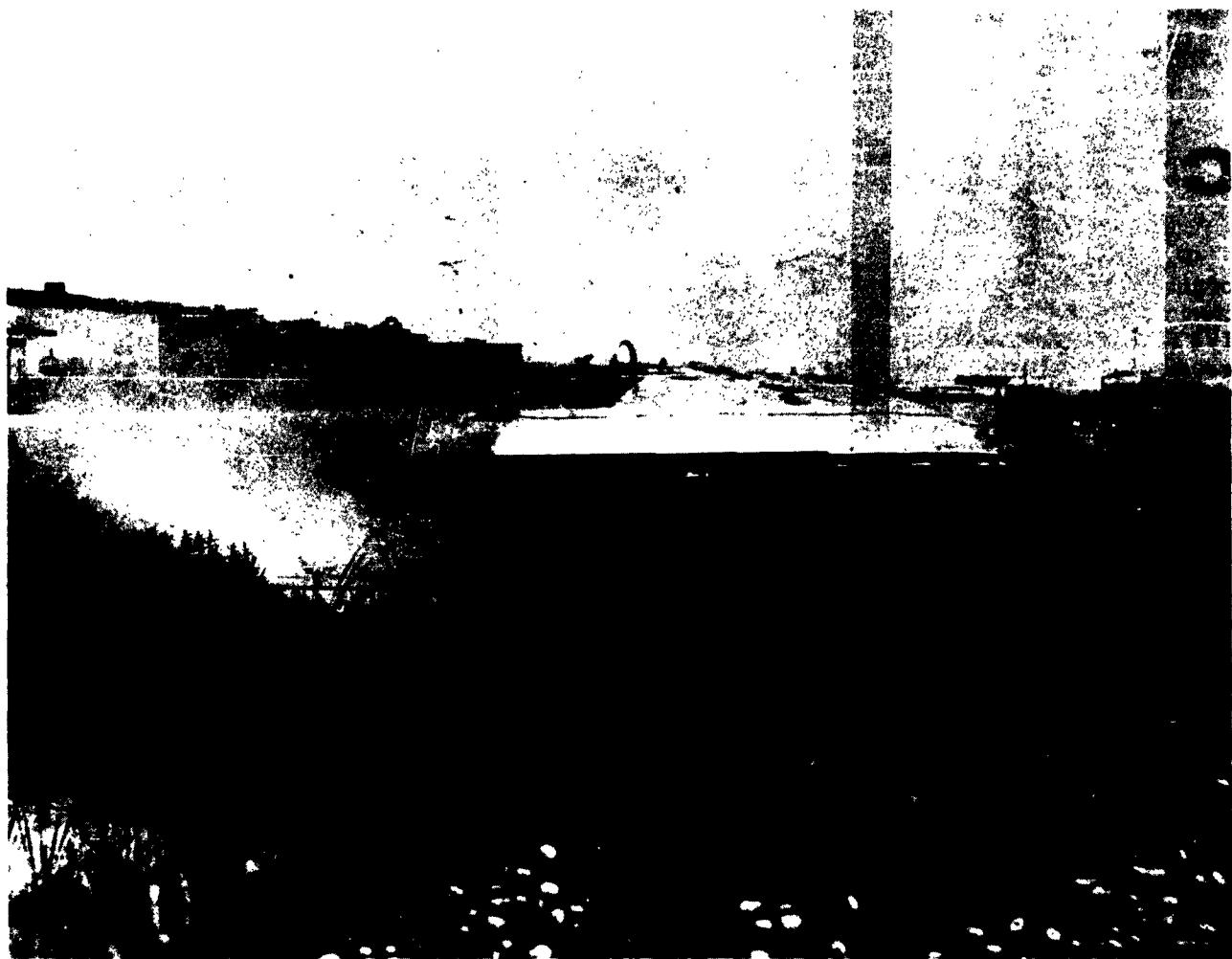


FIGURE 9
AVROCAR CROSSING THE LARGE DITCH.
AIR SPEED ABOUT 10 KNOTS. NOTE AVROCAR
IS ABOUT $\frac{1}{2}$ OVER FIRST EDGE OF THE
DITCH BUT AIRCRAFT IS STILL LEVEL

CONCLUSIONS



Performance, stability and control of the Avrocar in its present configuration restrict the hovering height to about 1½ feet and prevent accelerating in ground effect to a free air flight speed. Incorporation of the high speed flight control system adversely affected the performance and controllability of the Avrocar during hovering and low speed flight.

The decrease in hovering performance is partly due to a decrease in the efficiency of the duct leading to the annular nozzle.

Longitudinal and lateral control power is much less than that available before the modifications. This is primarily because the modified focussing ring suspension increased the hinge moment which decreased control travel. The control system is pneumatic and the resulting force, with the maximum allowable air pressure, was not sufficient to overcome the increased hinge moment. The decreased focussing ring travel has also decreased maximum level flight airspeed from 30 to 20 knots.

Relocation of the yaw control vanes from the previous lateral location to the

forward sections of the fuselage has resulted in severe longitudinal-directional control coupling.

Incorporation of the high speed flight controls has not significantly changed the stability characteristics of the Avrocar during hover and low speed flight.

Low speed flight with mild asymmetric power conditions is feasible. However, lack of control would prohibit flight with one engine inoperative.

The Avrocar can negotiate small slopes and cross relatively large ditches although recirculation is a major problem when flying over unprepared terrain; however, the lack of protection for the focussing ring is also considered a major problem due to the possibility of contacting the edge of the ditch.

None of the deficiencies seriously restrict research and development testing in the 0 to 15 knot regime. Control limitations presently prohibit flight testing in the transitional or high speed regime.

RECOMMENDATIONS

A Performance, stability and control of the Avrocar in its present configuration prevents accelerating in ground effect to a free air flight speed. Full scale wind tunnel results indicate that sufficient control is available to conduct a transition into high speed flight (about 100 knots IAS maximum), provided that 35 to 40 knots can be obtained with the focussing ring control system. If the decision is made to continue the Avrocar program to demonstrate ground effect take-off and landing it is recommended that the following be accomplished:

1. Install instrumentation to measure performance, stability, and control parameters (page 1).
2. Increase the travel of the focussing ring to increase controllability. This will require incorporation of a hydraulic control system or equivalent to overcome the high hinge moment and/or modification of the focussing ring suspension system to reduce the hinge moment (page 12).

3. Increase performance so that the aircraft can hover at least 3 to 4 feet above the ground. Performance could be increased by reducing the turborotor turbine blade tip clearance and increasing duct efficiencies by modifying the transition doors, installing guide vanes about the corners, extending the engine exhaust ducts, sealing the holes in the ducts through which the control cables pass, increasing the number of stators below the turborotor, and straightening the duct and optimizing the cross sectional area of the duct just upstream of the annular nozzle (page 10,12).
4. Re-align the cockpit so that the pilot is facing the direction of flight (page 8).
5. Provide foot pedals for directional control (page 8).
6. Provide protection for the focussing ring control to prevent

contact with the ground over uneven terrain (page 16).

B The Avrocar can be used in its present configuration for evaluating problems peculiar to ground effect machines in hovering and low speed flight. The aircraft can easily be instrumented to obtain quantitative results. It is recommended that studies be initiated to determine if requirements exist for qualitative definition of one or more of the following:

1. Ground cushion instability at critical height (page 10).
2. Control and damping requirements for maneuvering flight (page 13).
3. Variation of focussing ring control power with hovering height, engine power, and/or gross weight (page 9,12).

4. Effect of center of gravity location on control and stability derivatives (page 12,15).

5. Linear accelerations available from a focussing ring control system (page 12).

6. Effectiveness of the automatic gyro stabilization system (page 7).

7. Effect of various types of unprepared terrain on performance (page 15).

8. Control requirements for hovering over and crossing various types of irregular terrain (page 15).

9. Aircraft behavior in gusty winds (page 10,13).

10. Aircraft characteristics during flight over a large body of water (page 15).

APPENDIX I

general aircraft information

AIRFRAME

Diameter or wing span	18 ft
Gross wing area	254 sq ft
Aspect ratio	1.27
Thickness/chord ratio	20%
Wing loading at 5650 pounds gross weight	22.2 lb/sq ft

Wing section is symmetrical about vertical centerline and elliptical in profile.

POWER PLANT

Manufacture	Continental
Type	J69-T-9
Number	3
Static thrust, sea level	927 lb
Gas generator speed	22,700 rpm
Gas generator mass flow	55.2 lb/sec
Overall diameter	27 in
Weight	364 lb
Maximum fuel capacity, total of the three tanks	177 US gals

TURBOROTOR

Manufacture	Orenda Engines Limited
Type	Single stage axial flow fan
Speed, maximum rating	2570 rpm
Fan inner diameter	20.18 in
Fan outer diameter	60.0 in
Number of blades	31
Blade chord (constant)	4.1 in
Thickness/chord ratio, hub tip	13% 8%
Maximum rotor tip Mach number	0.78
Total weight including stator, shroud, and seal	338 lb
Turbine drive	
number of nozzles	144
number of turbine blades	124
chord of turbine blade	
turbine blade tip diameter (constant)	2 in
	65.0 in